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USAARL Report No. 94-46

Temporary Threshold Shifts Produced by High Intensity Freefield Impulse Noise in Humans Wearing Hearing Protection

(Reprint)

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August 1994

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United States Army Aeromedical Research Laboratory
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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release, distribution unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S) USAARL Report No. 94-46	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Aeromedical Research Laboratory 6b. OFFICE SYMBOL (If applicable) SGRD-UAS-AS	7a. NAME OF MONITORING ORGANIZATION U.S. Army Medical Research, Development, Acquisition and Logistics Command
6c. ADDRESS (City, State, and ZIP Code) P.O. Box 620577 Fort Rucker, AL 36362-0577	7b. ADDRESS (City, State, and ZIP Code) Fort Detrick Frederick, MD 21702-5012
8a. NAME OF FUNDING / SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 62787A PROJECT NO. 30162787A878 TASK NO. I WORK UNIT ACCESSION NO. 285

11. TITLE (Include Security Classification)
Temporary threshold shifts produced by high intensity freefield impulse noise in humans wearing hearing protection

12. PERSONAL AUTHOR(S)
James H. Patterson, Jr., and Daniel L. Johnson

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM ______ TO ______	1994 August	16

16. SUPPLEMENTARY NOTATION
This was published in the Proceedings of the V:th International Symposium, Effects of Noise on Hearing, Gothenburg, Sweden, 12-14 May, 1994.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	impulse noise, hearing protection, exposure limits, freefield impulse noise
20	14		
06	04		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Exposure to high intensity impulse noise produced by modern military weapons is known to be hazardous to hearing. Hearing protection is required; however, there is no generally accepted theoretical way to predict whether protection will be adequate for the highest noise levels. This had led us to empirically determine the safe limits of exposure to impulse noise when hearing protection is used by exposing human volunteers under controlled conditions. Over the past 5 years, a series of studies has been conducted to determine the maximum safe exposure to high intensity freefield impulse noise. An exposure was considered to be safe if it produced only a small temporary threshold shift (TTS < 25 dB) in a small percentage of the volunteers exposed. Three different impulses were used with A-durations of 0.8, 1.4, and 2.9 ms. Both the level and number of impulses were varied to find the maximum tolerable exposure for combinations of these parameters. The peak sound pressure levels ranged up to 196 dB. The number of impulses was varied from 6 to 100. Approximately 60 volunteers were exposed to each type of impulse, allowing high confidence estimates of the exposures which

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20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Chief, Science Support Center	22b. TELEPHONE (Include Area Code) 205-255-690 22c. OFFICE SYMBOL SGRD-UAX-SI

19. Abstract (Continued):

would produce no significant TTS in 95 percent of the exposed population. The hearing protection used was an ear muff which had been modified to simulate a poor fitting protector. The results of these studies indicated that even with a relatively poor hearing protector, combinations of level and number of impulses which far exceed our currently accepted exposure limits could be tolerated by 95 percent of the volunteers.

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Introduction

Over the past several years, the U.S. Army Medical Research, Development, Acquisition and Logistics Command (USAMRDALC) has sponsored a series of studies to determine the human tolerance limits of exposure to high-intensity freefield impulse noise. These studies have been conducted at the Blast Overpressure Test Site in Albuquerque, New Mexico, by EG&G Management Systems, Inc. The goal of these studies was to provide information relevant to the maximum safe exposure limits for various heavy weapons: towed artillery, mortars and shoulder fired antiarmor weapons. Pfander (1975) reported the results of temporary threshold shift (TTS) studies in which soldiers were exposed to the noise of various weapons. More recently, Patterson et al. (1985), Patterson and Mozo (1987), and Dancer et al. (1992), reported studies designed to determine TTS in volunteers exposed to artillery and antiarmor weapons. These studies all demonstrated that specific weapons could be fired safely with hearing protection. However, they did not establish new limits for impulse noise exposure since essentially no effects on hearing were found.

In addition to effects on hearing, high intensity blast can injure other organ systems. The air containing organs seem to be the next most susceptible organs after the inner ears. Dodd et al. (1990) proposed limits for exposure to blast with minimal risk of upper airway, lung, and gastrointestinal injury. These limits are well above the blast limits in current weapons design standards in the United States (Department of Defense, 1979). The studies reported here were designed to use exposures to levels beyond any which had been used previously in experiments on humans in order to determine the exposures which would produce an effect on hearing. The exposures were limited only by the limits for nonauditory injury.

Methods

The basic approach of the studies was to expose human volunteers to a progression of increasingly more energetic impulse noise stimuli. Hearing protection was worn during all exposures. Temporary changes in hearing threshold (TTS) were used as the basic indicator of adverse effects on hearing. All exposure stimuli were produced by the detonation of high explosives. Three different exposure configurations were used to vary the duration of the impulse by changing the distance between the explosive source and volunteers. The first configuration placed the volunteers 5 meters from the detonation. This produced a pressure-time signature (Figure 1, panel a) characteristic of towed artillery. The A-duration was approximately 2.9 milliseconds. The second configuration placed the volunteers 3 meters from the explosive source. This produced a pressure signature (Figure 1, panel b) with a 1.5 millisecond A-duration. The third configuration placed the volunteers within 1 meter of the source. This produced an impulse with a 0.8 millisecond A-duration (Figure 1, panel c). Since the A-duration of a freefield impulse strongly influences the distribution of energy across frequency, the three configurations produced exposure stimuli with different energy density spectra. Figure 2 shows the spectra of the three impulses. The pressure-time signatures with the longer A-duration have more low frequency energy in the spectrum.

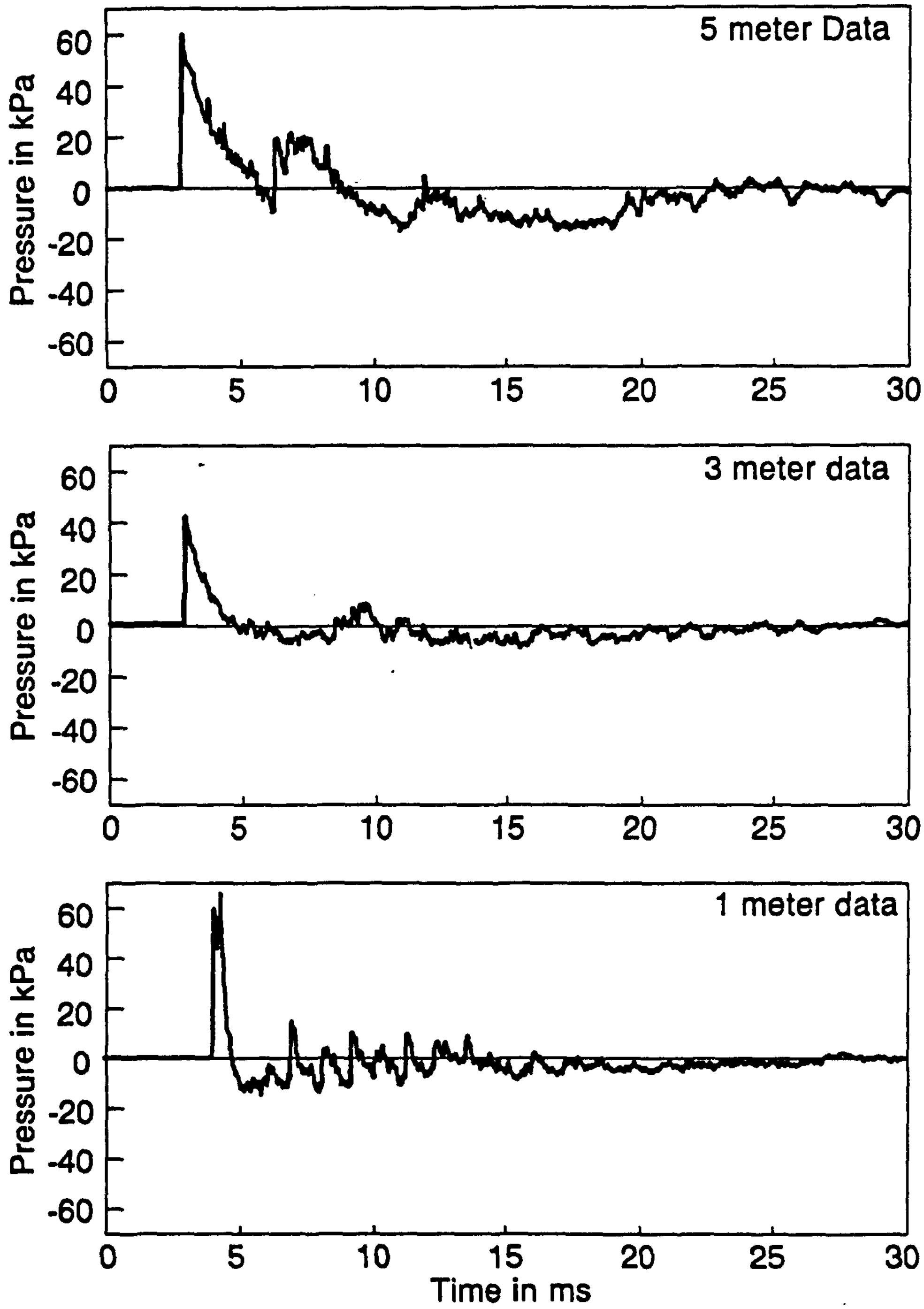

Figure 1. Pressure-time signatures at each of three distance conditions.

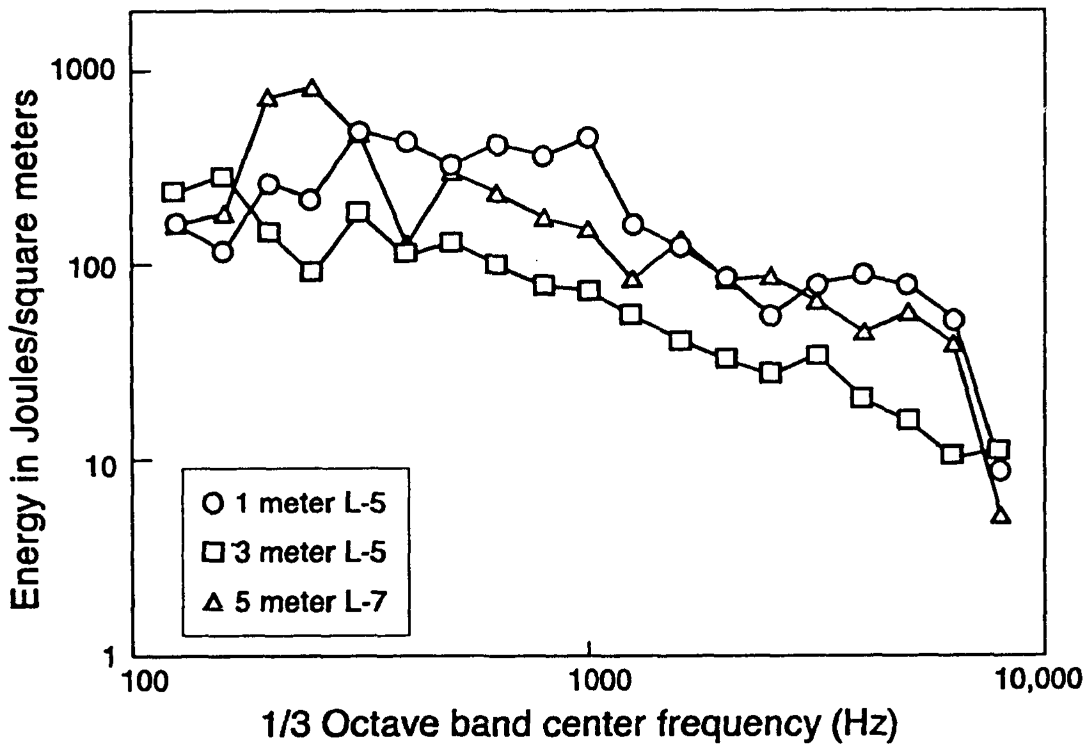

Figure 2. One-third octave band spectrum of the three impulses.

At least 59 volunteers were exposed to impulses at each distance configuration. The primary measure of effect on hearing was temporary threshold shift immediately after the exposure (2-6 minutes). A criterion of 25 dB TTS was adopted to define unacceptable effects on hearing. The intensity and number of impulses were varied to find the maximum exposure which would produce an unacceptable TTS in 5 percent of the exposed volunteers. The maximum intensities were set by the nonauditory injury limits derived by Dodd et al. (1990). The number of impulses per exposure was varied from 6 to 100.

Hearing protectors with two different attenuation characteristics were used in these studies. The first protector was an ear muff which is compatible with the U.S. Army infantry helmet. The attenuation of this hearing protector is shown in Figure 3 as the standard muff. It is comparable to other protectors commonly used in the military. The second protector was a modified version of the standard muff. The attenuation was reduced to simulate a poor fit. This was accomplished by inserting plastic tubes through the ear seals to introduce a controlled leak. The attenuation is shown in Figure 4. This modification resulted in essentially no attenuation below 500 Hz, and some amplification near 250 Hz due to resonance.

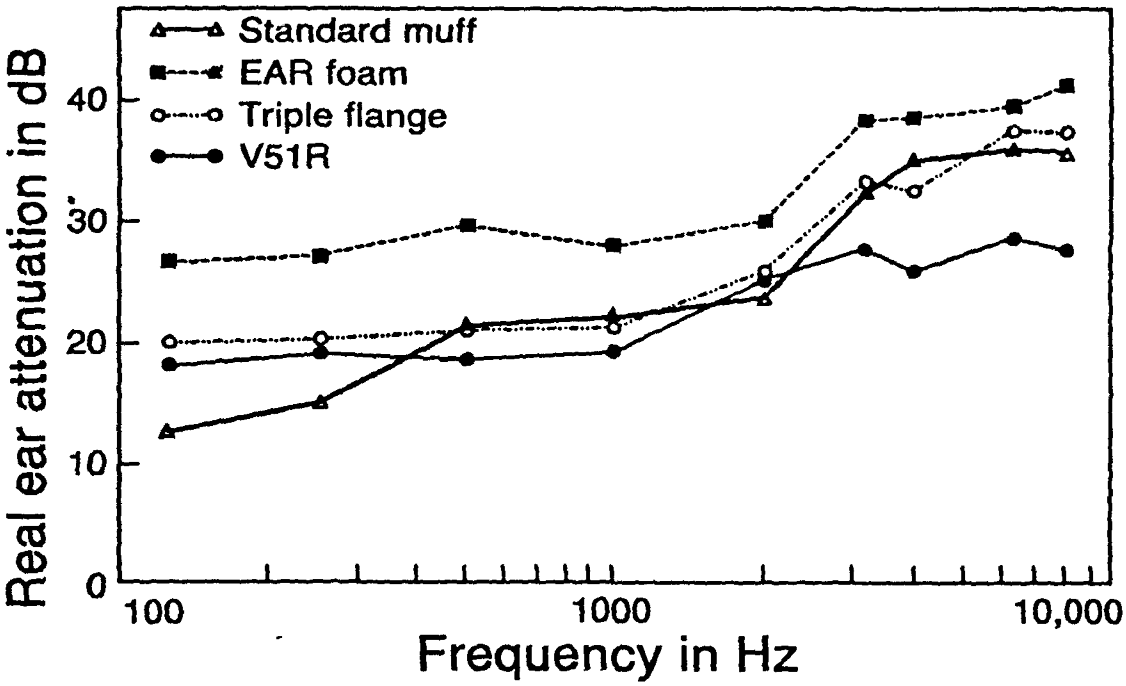

Figure 3. Attenuation of the standard earmuff compared to other hearing protectors used by the U.S. Army.

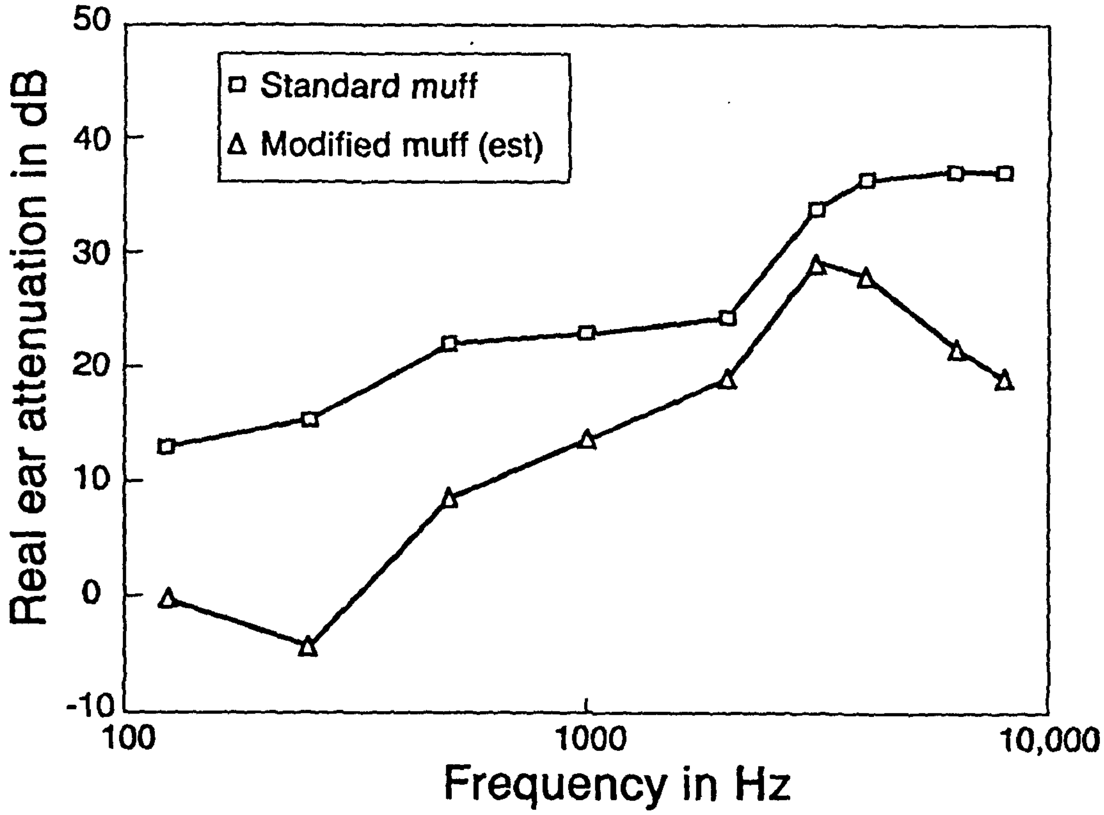

Figure 4. Attenuation of the standard ear muff and the modified ear muff.

Results and discussion

The results of these studies can be summarized as the percentage of volunteers showing unacceptable TTSs (i.e., TTS>25 db at any frequency) for each combination of intensity and number of impulses. In addition, we may calculate, using order statistics (Hogg and Craig, 1965), the confidence that no more than 5 percent of the population would exhibit a TTS exceeding 25 dB. The minimum sample size of 59 volunteers was calculated so that the largest TTS would provide a 95 percent confidence upper bound on the TTS at the 95th percentile of the population. Thus, if the largest TTS did not exceed 25 dB, we can be 95 percent confident that 95 percent of the population would not show a TTS larger than 25 dB. The second largest TTS then forms a lower confidence upper bound on the 95th percentile TTS. This sequence may be extended through all the subjects. As a matter of practicality, the confidence drops to approximately 5 percent at the 6th largest TTS. When 6 out of 59 volunteers show TTSs exceeding 25 dB, we can be 95 percent confident that the 95th percentile TTS also exceeds 25 dB.

Five-meter distance

Two groups of subjects were exposed at the 5-meter distance. The exposure levels ranged from 174 to 191 dB peak SPL. The first group wore the standard earmuff. None of the volunteers exposed at the 5-meter distance with the standard muff incurred a TTS in excess of 25 dB. In fact, none of the volunteers incurred even a 15 dB TTS.

Then, the 5-meter exposures were repeated on another group of volunteers wearing the modified muff. This time, TTS in excess of 25 dB was observed in a few volunteers at the most energetic conditions. Figure 5 shows the percentage of volunteers showing an unacceptable TTS. Note that even though we started with at least 59 volunteers in each group, the number varied across the studies. Also, as volunteers dropped out of a study, the number of volunteers at each exposure condition within the study varied. Figure 6 shows the confidence that 95 percent of the population would show an acceptable TTS. This incorporates the effects of both the number of volunteers and the number of unacceptable TTSs.

Three-meter distance

In the next study, another group of volunteers was exposed at the 3-meter distance to intensities ranging from 174 to 193 dB SPL with an A-duration of 1.5 ms. The number of impulses per exposure again was varied from 6 to 100. The hearing protection was the modified muff. The most energetic conditions again produced unacceptable TTS in some of the volunteers. Figure 7 shows the percentage of volunteers with an unacceptable TTS. In this case, the higher level impulses produced more unacceptable TTSs than at the 5-meter distance.

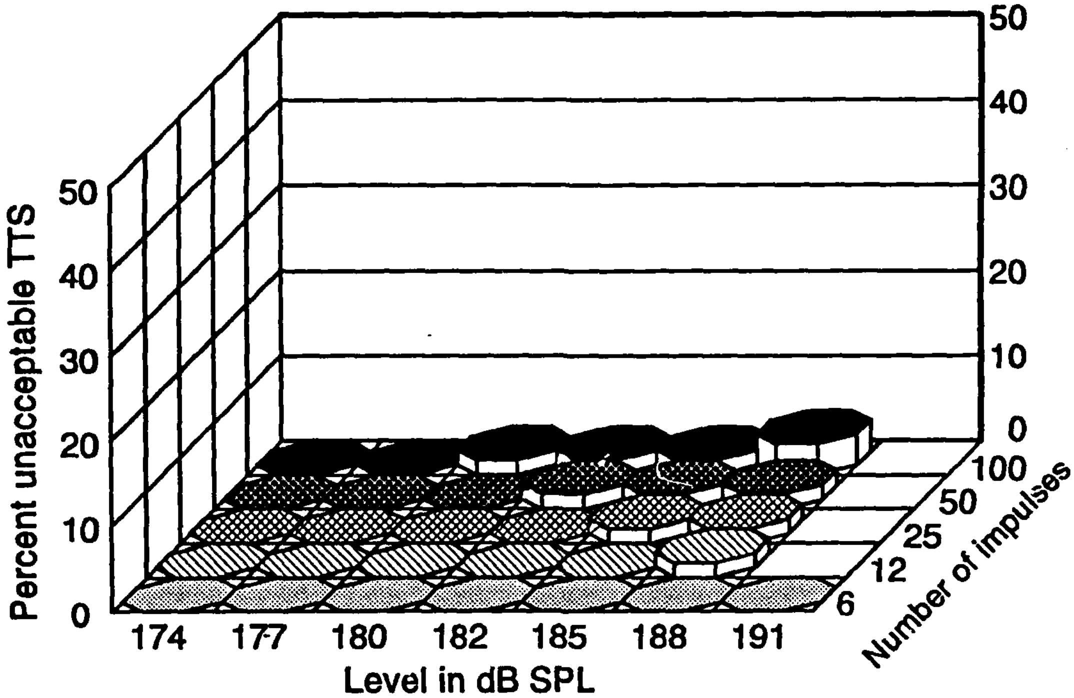

Figure 5. Percentage of volunteers showing an unacceptable TTS after exposure at the 5-meter distance while wearing the modified ear muff.

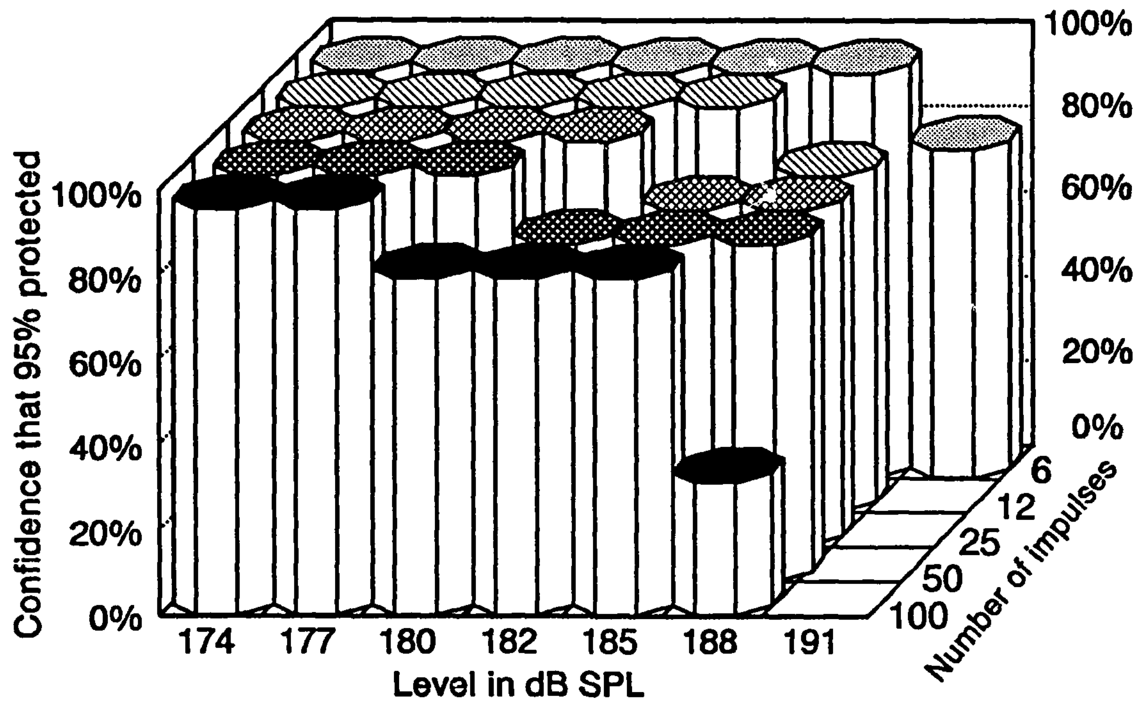

Figure 6. Percentage confidence that 95 percent of the exposed population would show an acceptable TTS after exposure at the 5-meter distance while wearing the modified earmuff.

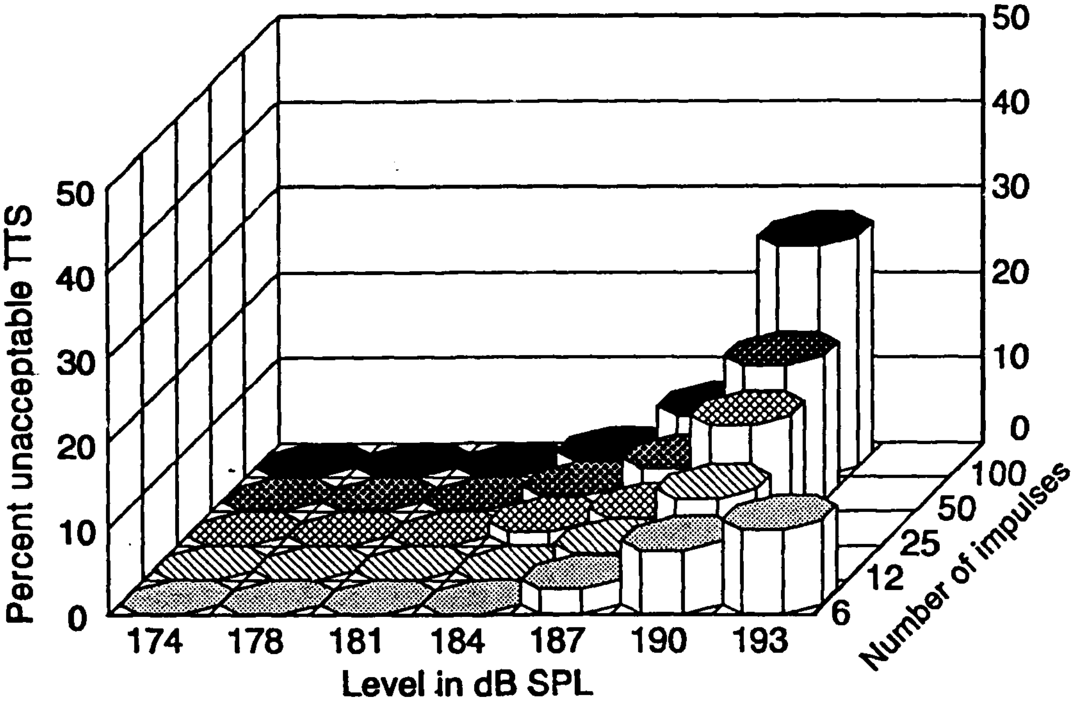

Figure 7. Percentage of volunteers showing an unacceptable TTS after exposure at the 3-meter distance while wearing the modified earmuff.

Five volunteers in this group were prevented from proceeding to more energetic conditions because of unusual recovery patterns. These included either recovery times longer than 24 hours, or a pattern of growth of TTS during the first 24 hours. The data for these volunteers were included for all conditions in which they participated. As a result, the data in the 25-, 50-, and 100-shot conditions probably show fewer unacceptable TTSs than would have occurred if these volunteers had been allowed to continue in the study. While it is difficult to estimate the effect these volunteers may have had on the data, it is unlikely that they would have reduced the maximum safe exposure levels (discussed below) more than 3 dB for 100 shots.

Figure 8 shows the confidence that 95 percent of the population would have a TTS less than 25 dB. These data also are influenced by the discontinued volunteers.

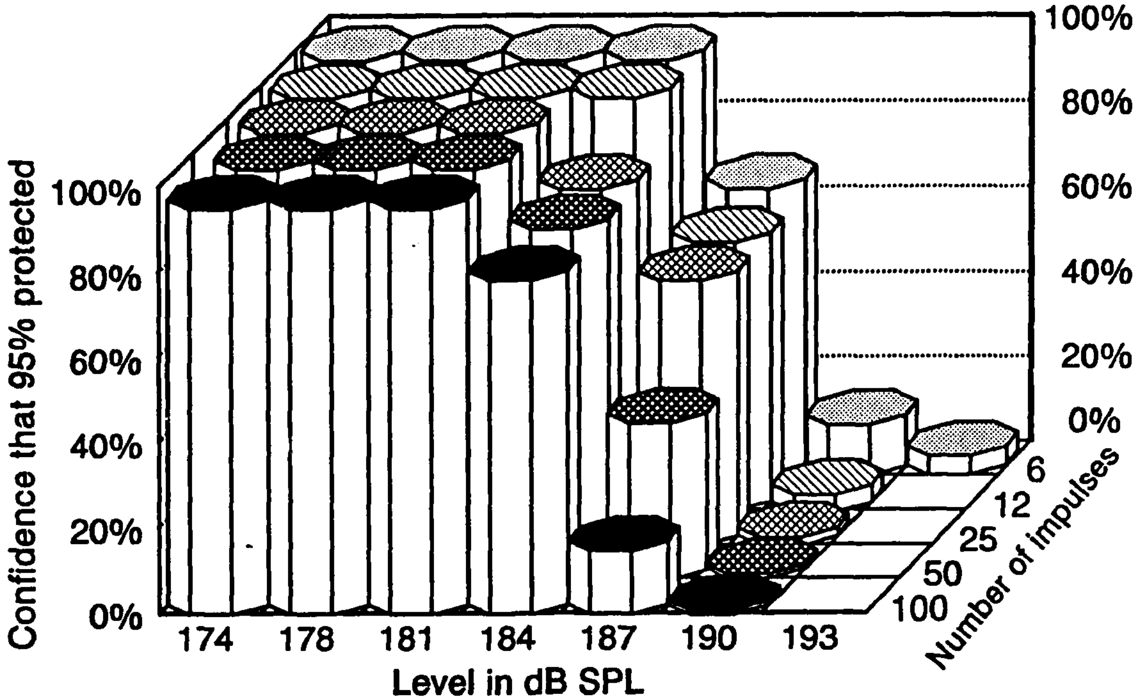

Figure 8. Percentage confidence that 95 percent of the exposed population would show an acceptable TTS after exposure at the 3-meter distance while wearing the modified earmuff.

One-meter distance

At the 1-meter distance, the peak pressures were varied from 178 to 196 dB peak SPL, with A-durations of 0.8 ms. In this study, the number of impulses per exposure also was varied from 6 to 100 and the volunteers wore the modified muff. Figure 9 shows the percentage of volunteers showing a TTS in excess of 25 dB. In this case, five volunteers also were prevented from completing all exposures. Therefore, the comments about potential effects on the data in the 3-meter section also apply to the data from this distance. The confidence that 95 percent of the population exposed to this impulse would show less that 25 dB TTS is shown in Figure 10.

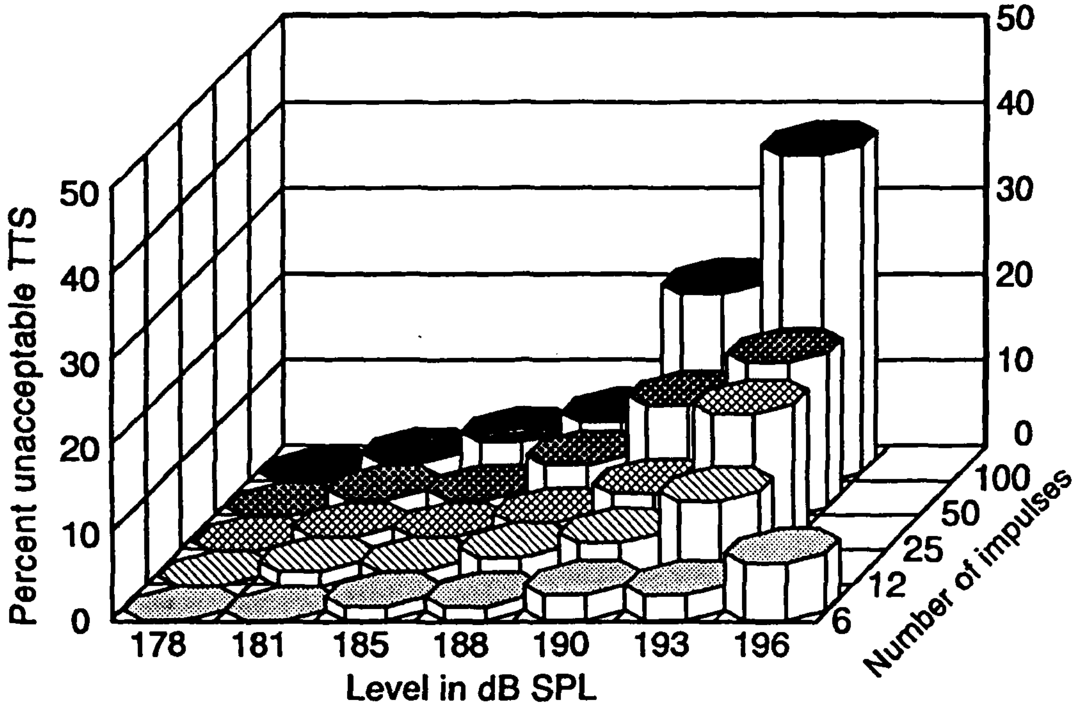

Figure 9. Percentage of volunteers showing an unacceptable TTS after exposure at the 1 meter distance while wearing the modified earmuff.

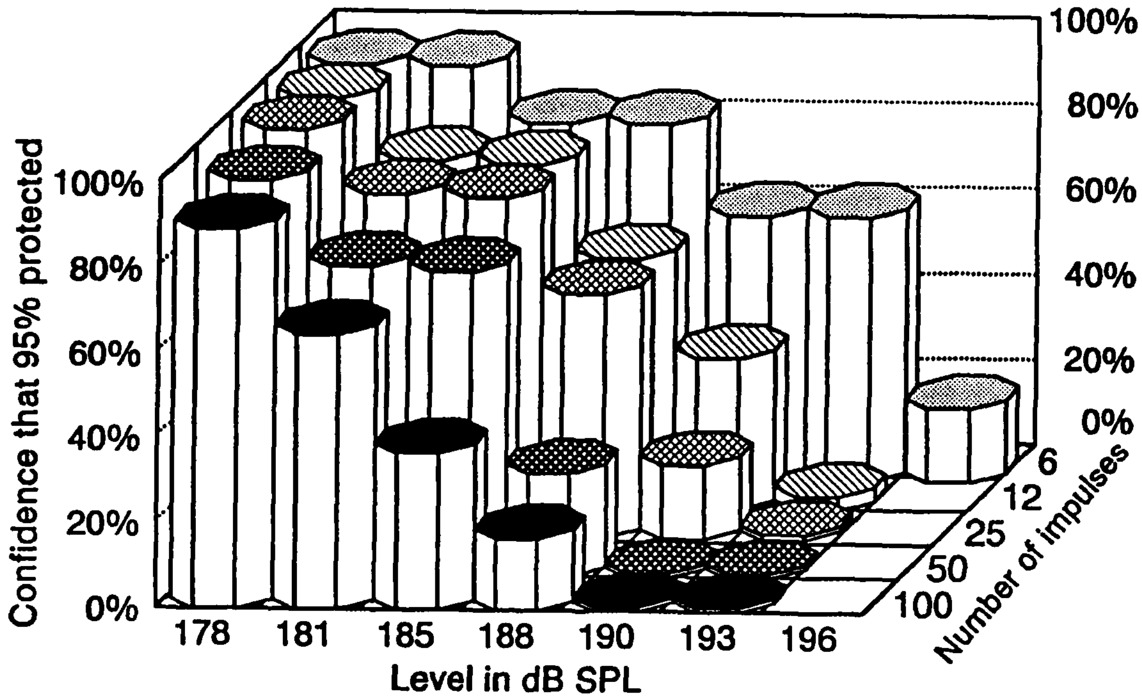

Figure 10. Percentage confidence that 95 percent of the exposed population would show an acceptable TTS after exposure at the 1-meter distance while wearing the modified ear muff.

Development of safe levels

There are several ways to derive maximum safe exposure levels from the TTS data. Each combination of intensity level and number of impulses defines an exposure condition. One way to estimate the maximum safe exposure levels is to find the set of exposure conditions for each distance which resulted in unacceptable TTS in less than 5 percent of the exposed population (see Figures 5, 7, and 9). The maximum safe exposure levels come from the exposure condition with the highest intensity level for each number of impulses for which less than 5 percent of the volunteers showed an unacceptable TTS. Table 1 contains these levels for all three exposure distances.

Table 1.
Maximum exposure levels resulting in at least 95 percent acceptable TTS.

	Exposure condition		
Number of impulses	5 meter	3 meter	1 meter
6	191[na]	187	193
12	188[na]	187	190
25	188[na]	187	188
50	187[na]	187	185
100	187[na]	184	185

[na] Nonauditory limits

An alternative way to estimate the maximum safe exposure levels is to use the percentage confidence that 95 percent of the exposed population would show an acceptable TTS. To do this we must select a percentage confidence to use is defining safe exposure conditions. If we require high confidence (e.g., 95 percent), the estimated safe levels will be lower. If we choose a low confidence (e.g., 5 percent), the estimated safe levels will be higher. By choosing a medium value of 50 percent confidence, we balance these extremes. Then, the maximum safe exposure levels come from the exposure conditions with the highest intensity level for each number of impulses for which the percent confidence that 95 percent of the exposed population would show an acceptable TTS is greater than 50 percent (see Figures 6, 8, and 10). These levels are shown in Table 2.

Table 2.
Maximum exposure levels resulting in greater than 50 percent confidence that 95 percent of the population show acceptable TTS.

Number of impulses	Exposure condition 5 meter	3 meter	1 meter
6	191[na]	187	193
12	188[na]	187	188
25	188[na]	187	188
50	187[na]	184	185
100	185	184	181

[na] Nonauditory limits

As can be seen, there are some differences between these two approaches. However, these differences are no more than one level step in the exposure series used at each distance. Since the number of subjects actually showing an unacceptable TTS was small, these differences probably are statistical fluctuations. Since the percent confidence incorporates both the number of individuals showing a significant TTS, and the statistical effect of the number of volunteers included in each exposure condition, it seems reasonable to use the maximum safe exposure levels in Table 2.

The values from Table 2 are shown in Figure 11 with the Z-curve (5-shot limit) and the Y-curve (100-shot limit) from MIL-STD-1474. Note that the maximum safe exposure levels for various numbers of rounds derived from the studies reported here fall 5 to 15 dB above the respective limits from the military standard. There also appears to be a trend for the results from this study to slope upward with B-duration while the current Y- and Z-curve limits from MIL-STD-1474 slope downward with B-duration. This suggests that the peak level and B-duration are not good indicators of auditory hazard.

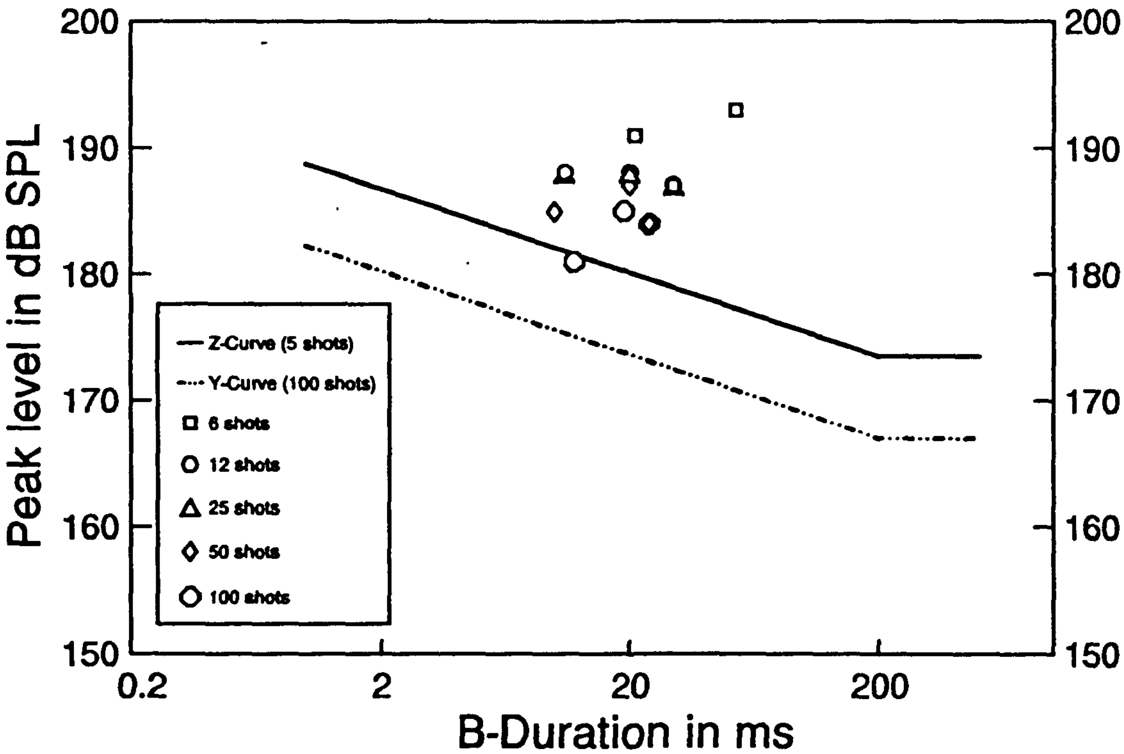

Figure 11. Comparison of maximum acceptable exposure levels with U.S. MIL-STD-1474C.

Conclusions

The results of these studies clearly indicate an earmuff can provide hearing protection for freefield blast levels which greatly exceed our current exposure limits. The use of modified muffs in these studies simulates the commonly occurring situation in which earmuffs do not fit properly, e.g., eye glasses temple pieces, long hair, or head gear can compromise the ear seal. Thus, the results should apply to a variety of real world exposure situations. Therefore, we may conclude from these studies that even poorly fit earmuffs can provide adequate protection against heavy weapons noise in the range of 181 to 194 dB peak SPL.

While the results of these studies clearly show that current military exposure limits are too restrictive, the replacement limits are not yet defined. In all likelihood, the new limit for freefield impulses will depend on the spectrum of the impulse, the attenuation characteristic of the hearing protector, and the number of impulses. How these factors will interact to produce the exact exposure limits still is being explored.

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